An Age Constraint on the Giant Impact from Lunar Sample Chronology

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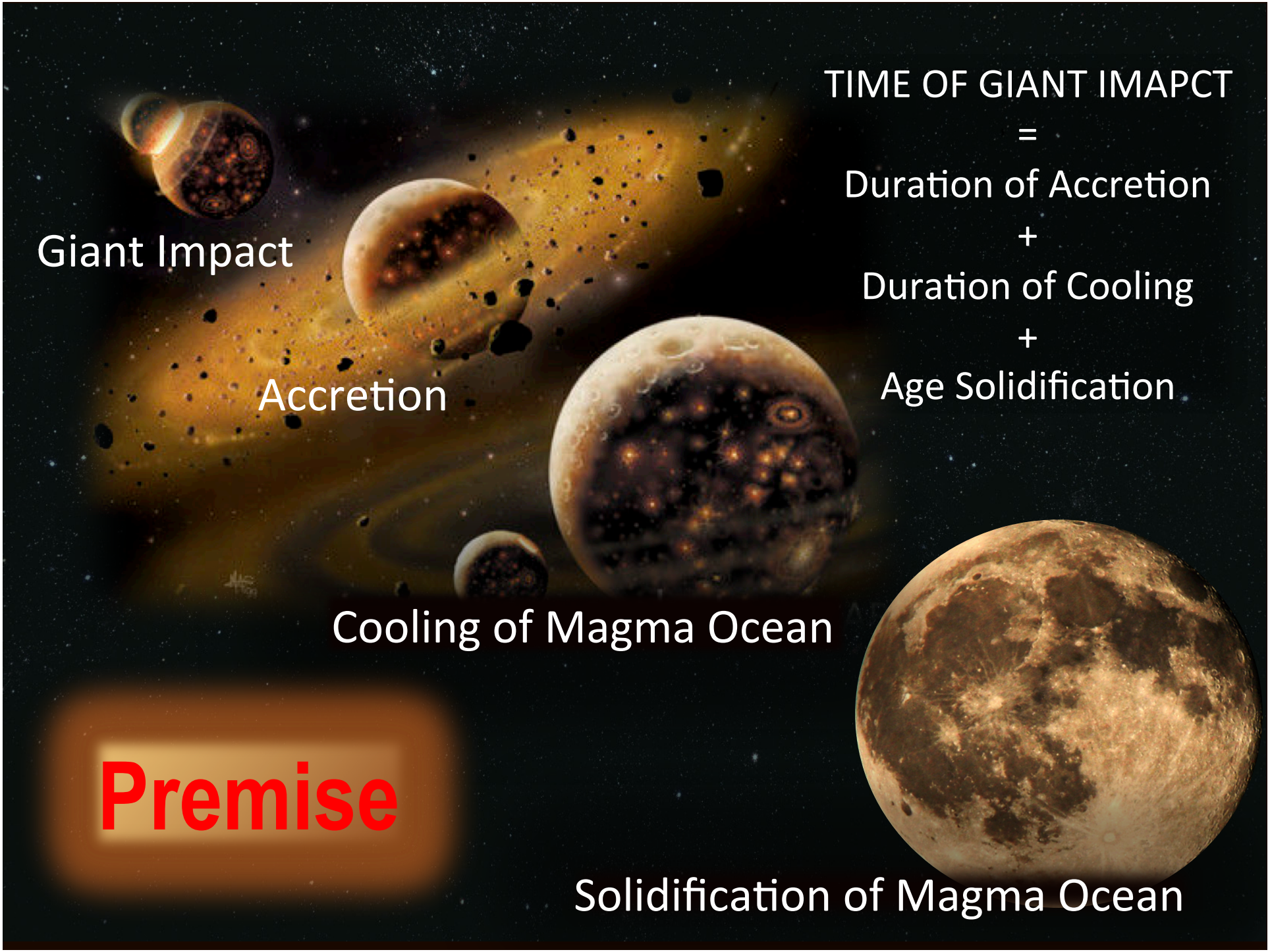
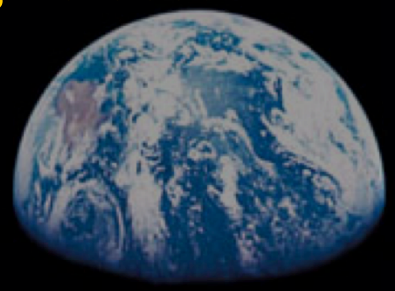
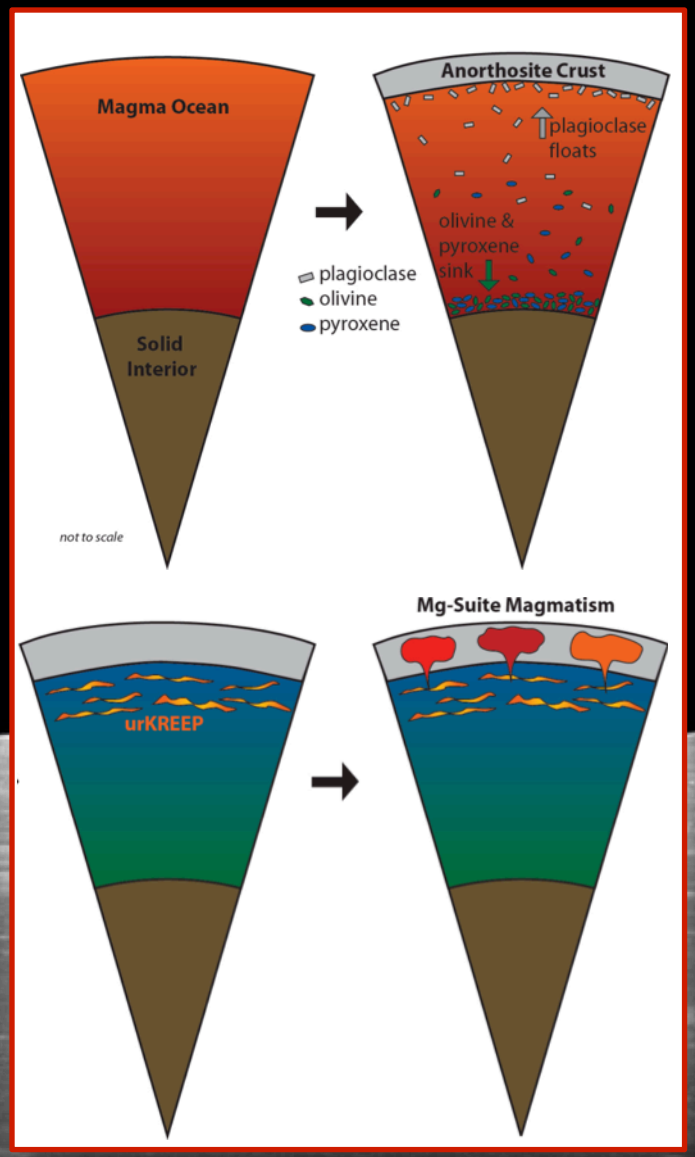

TIME OF GIANT IMAPCT
=
Duration of Accretion
+
Duration of Cooling
+
Age Solidification
Giant Impact
Accretion
Cooling of Magma Ocean
Premise
Solidification of Magma Ocean

Generic Magma Ocean Model

- Petrogenetic framework for lunar differentiation is the magma ocean model



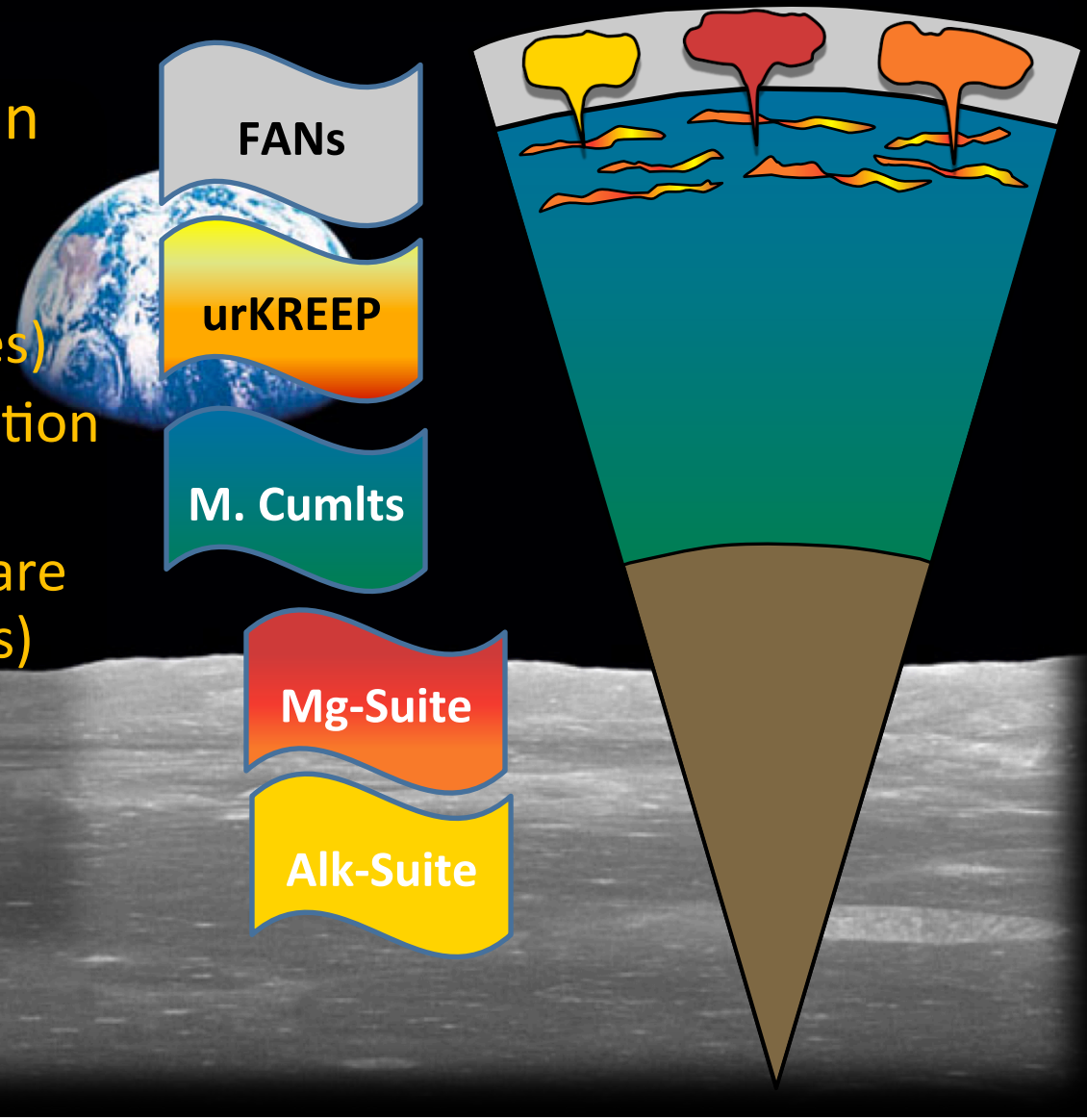
- Deduced from:
  - Widespread anorthosites on surface
  - Composition of anorthosites and KREEP-rich lunar samples
  - Experimental investigations of basalt source regions



Age of Solidification of Moon

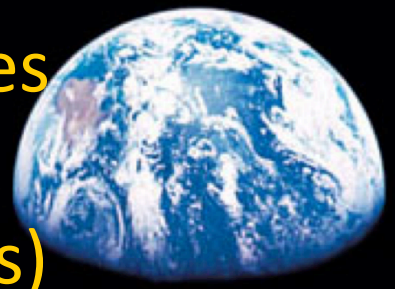
Rocks that that constrain age LMO solidification

- Felsic cumulates (Ferroan anorthosites)
- Late stage crystallization products (urKREEP)
- Mafic cumulates (Mare basalt source regions)
- Mg-suite and Alkali rocks (intruded into primary crust)



Range of Ages of Lunar Reservoirs

• FANS	4.29 to 4.56 Ga
• Mare basalt sources	4.32 to 4.38 Ga
• urKREEP	4.32 to 4.49 Ga
• Alkali suite (Zircons)	3.80 to 4.42 Ga
• Mg-suite	4.08 to 4.56 Ga

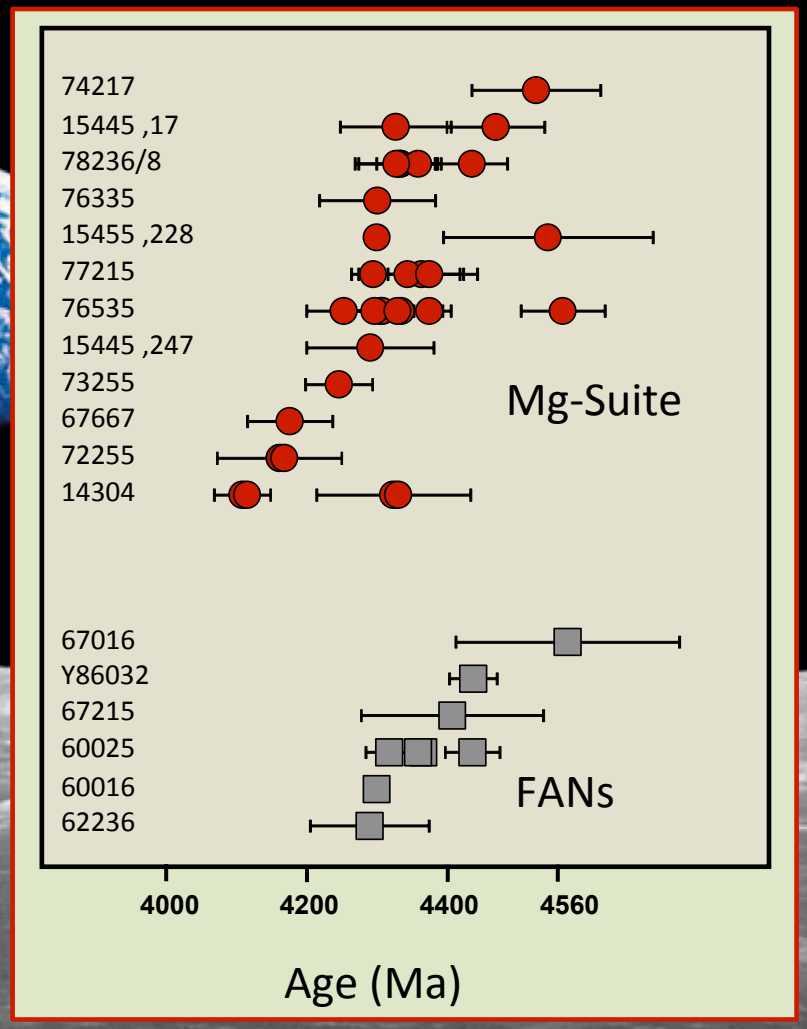


Large range of lunar reservoir ages do not allow them to provide significant constraints on primary solidification

Ages complied in Borg et al. (2015)

Individual Samples Yield Discordant Ages

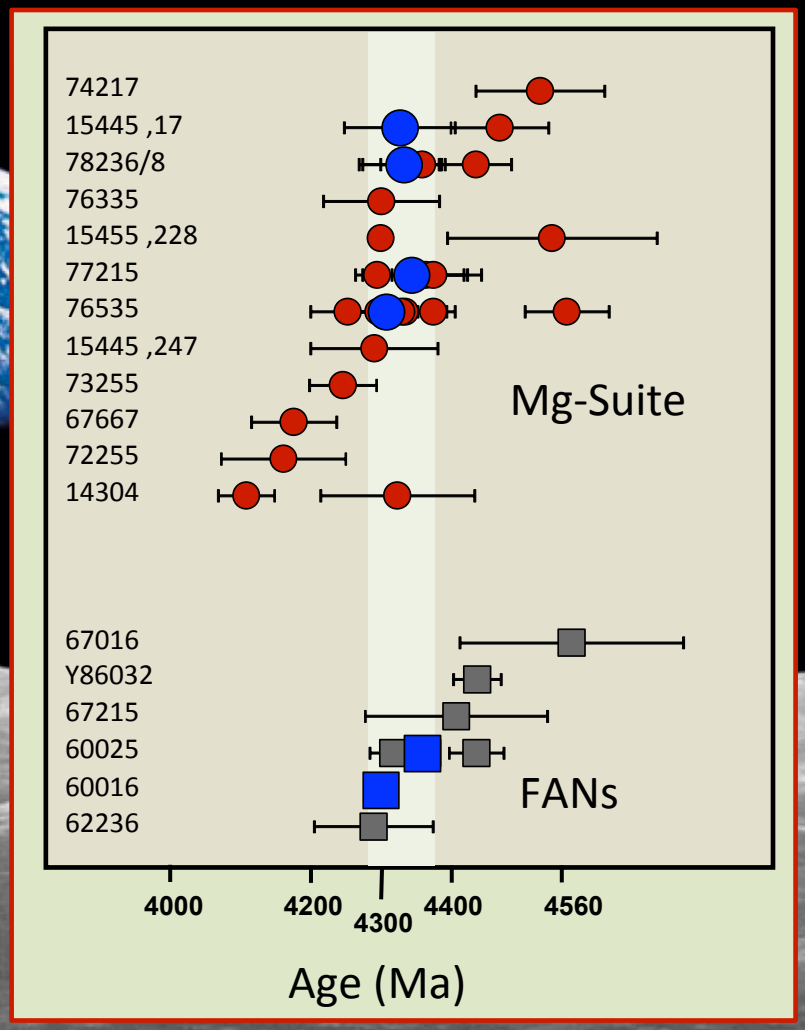
- All ages from 1975 to present
- Single samples yield multiple, discordant ages
- Most Samples dated using a single chronometer
- How reliable are ages determined by single chronometer?
- If all FAN ages reliable the LMO must cool over ~250 Ma



Borg et al. (2015)

Modern Techniques Provide New Insights

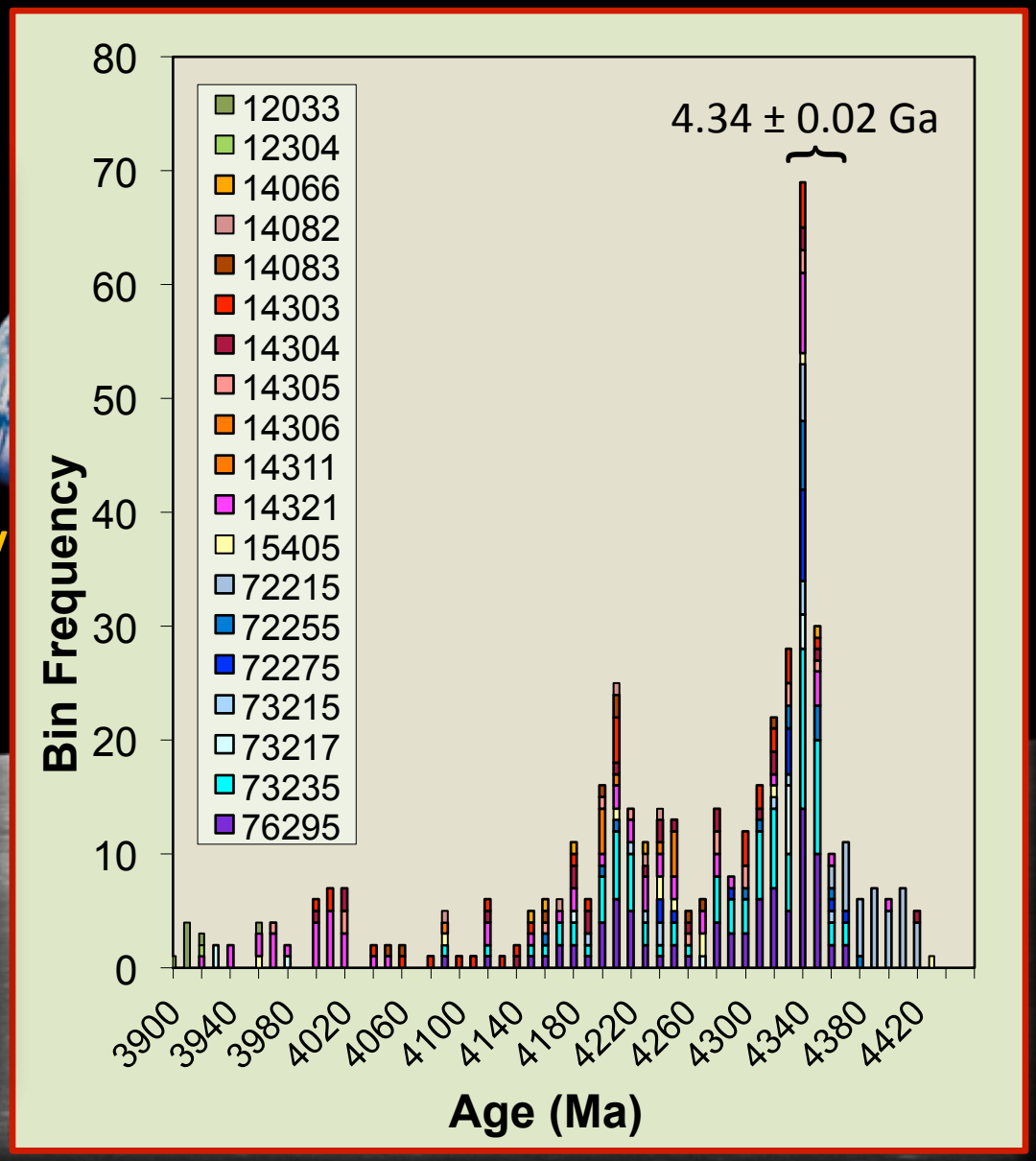
- Ages defined by average concordant values from multiple isotopic systems
- $^{146}Sm \rightarrow ^{142}Nd$, $^{147}Sm \rightarrow ^{143}Nd$, $^{176}Lu \rightarrow ^{176}Hf$, Pb-Pb, ^{87}Rb-^{87}Sr
- $^{146}Sm \rightarrow ^{142}Nd$ $t_{1/2}$ = 103 Ma is ideal to identify samples older than 4.45 Ga
- No old ages are not reproduced
- All ages roughly concordant at ~4.35 Ga



Borg et al. (2011, 2014), Absts. Gaffney et al. (2015), Marks et al. (2013)

Ages Alkali Suite Inferred from Zircon Spot Analyses

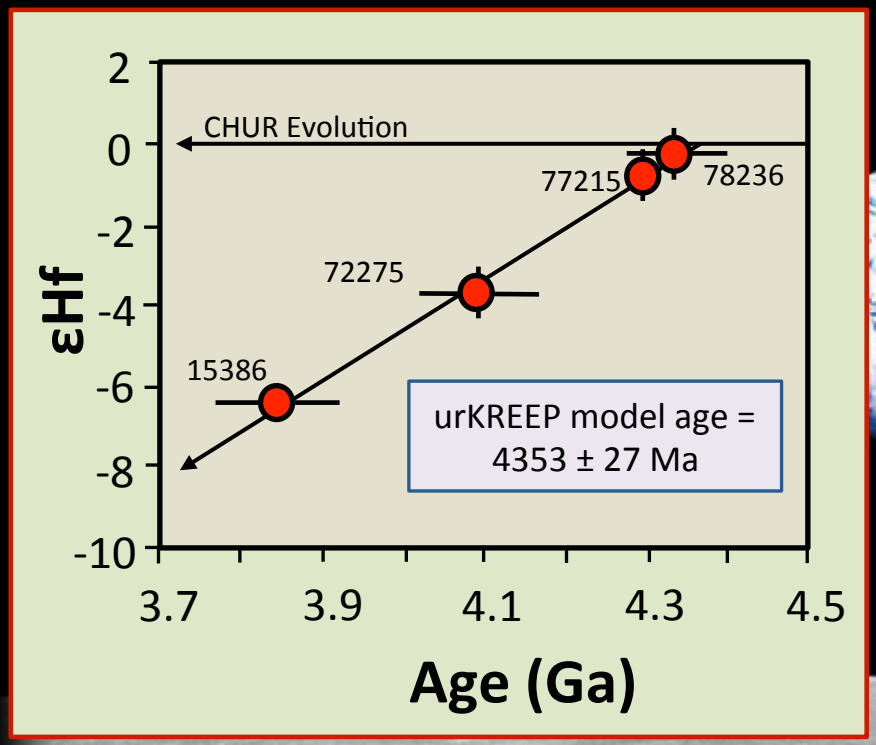
- Age range for alkali suite
  - Best determined by zircon spot ages
  - Young ages probably record late thermal metamorphism
  - Peak age is 4.34 ± 0.02 Ga
  - Few old ages- significance?

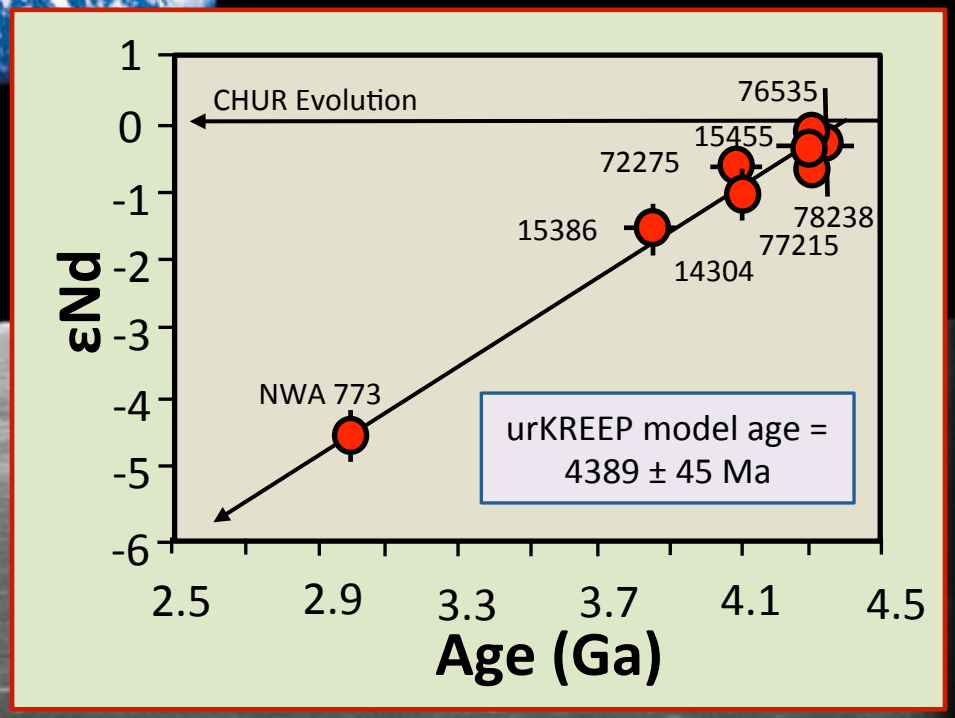


urKREEP Model Ages

urKREEP model ages defined from Sm-Nd and Lu-Hf isotopic systematics of KREEP-rich rocks

Sample demonstrate evidence they are undisturbed by post-crystallization processes

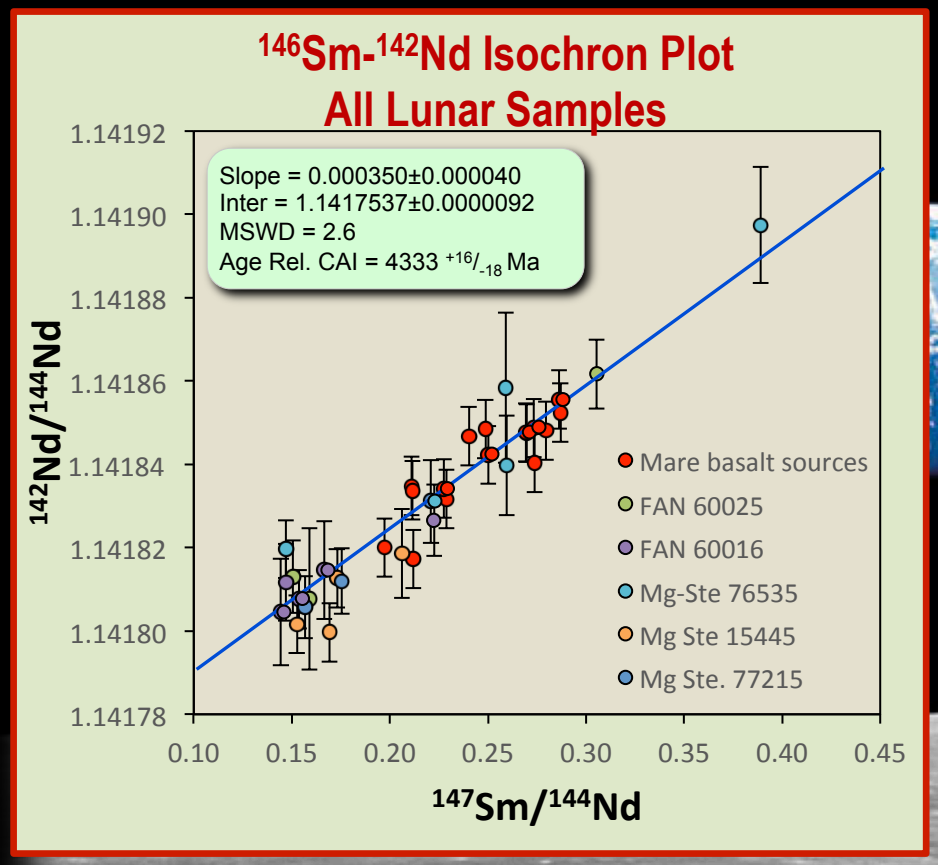




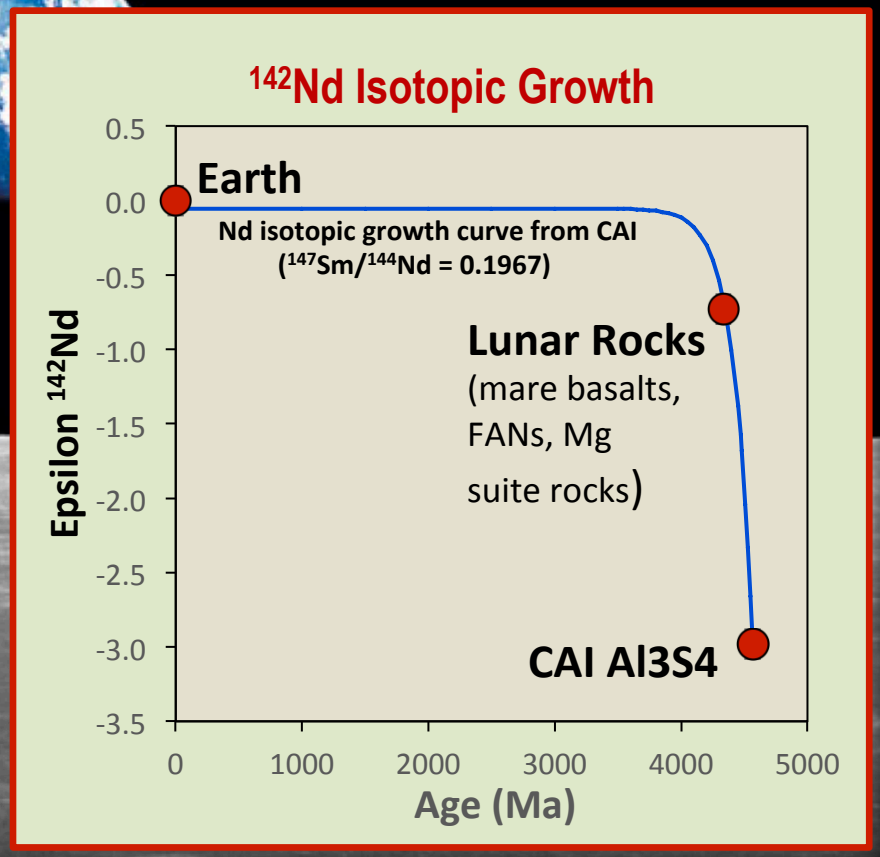
Concordant urKREEP model ages with average value of 4.37 ± 0.02 Ga

From Gaffney & Borg (2015)

Neodymium Isotopic Systematics



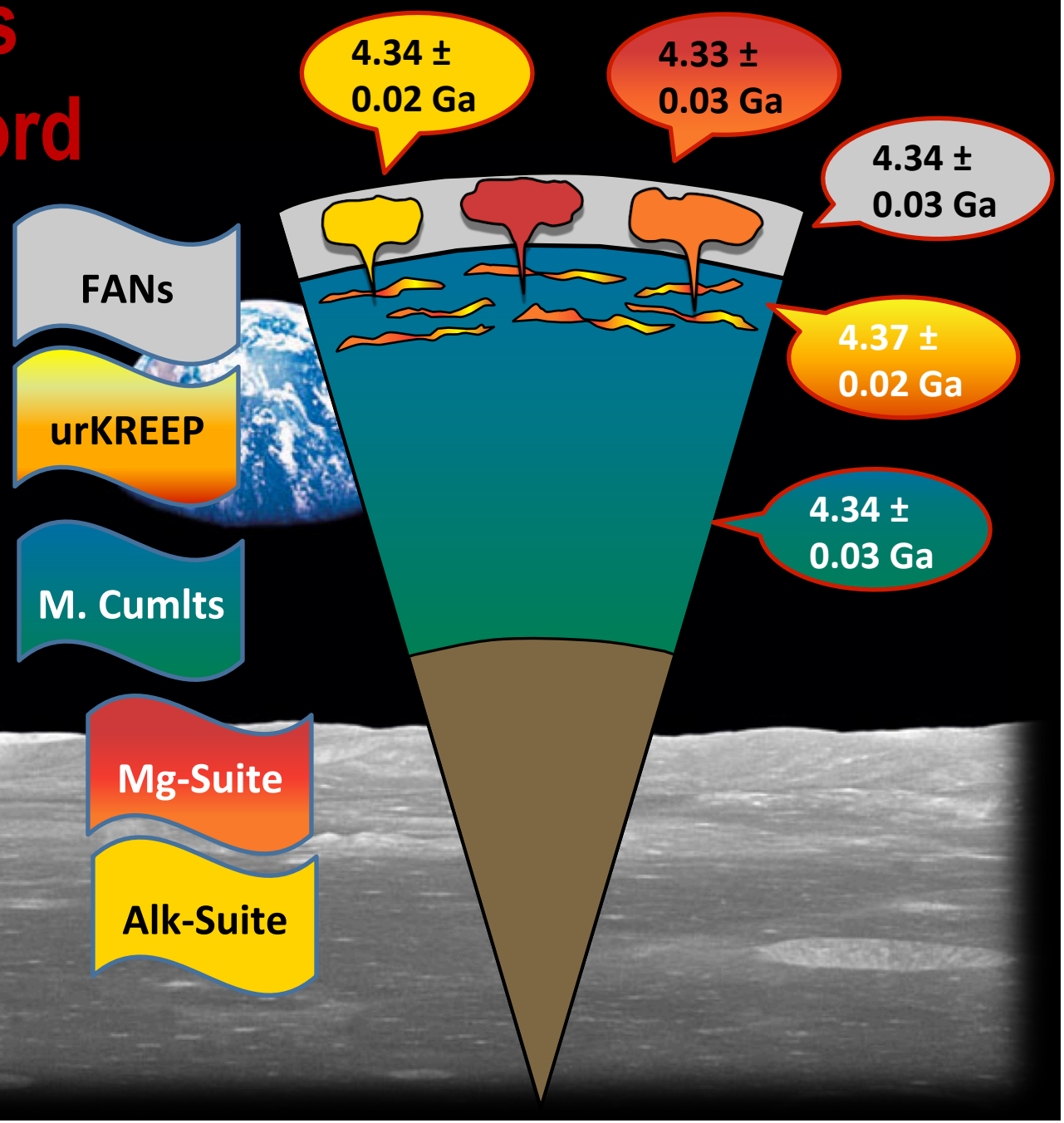
FANs, mare basalts, urKREEP, and Mg-suite derived from source with same Nd isotopic composition



Composition similar to that inferred for undifferentiated bulk Earth at ~4.33 Ga

Ages of Rocks that may Record Solidification of Moon

Best age determinations derived from average ages from multiple chronometers applied to multiple samples



Conclusions

- Most chronologic evidence suggests the Moon solidified at 4.34 ± 0.03 Ga
  - Ages of FANs, mare basalt source regions, urKREEP, Mg-suite, and most Alkali suite rocks are concordant at this age
  - All samples derived from reservoirs with same Nd isotopic composition
  - This reservoir is similar to best estimates of undifferentiated material at 4.34 Ga
- Implies
  - Giant Impact occurred late in Solar System history, or accretion of Moon after Impact was slow, or that the magma ocean remained molten for a period of long time
  - Giant impact occurred around 4.4 Ga (4.34 Ga + 0.05 Ga)